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How can we explore the onset of deconfinement by experiment?

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There is little doubt that Quantumchromodynamics (QCD) is the theory which describes strong interaction physics. Lattice gauge simulations of QCD predict that in the μ, T plane there is a line where a transition from confined hadronic matter to deconfined quarks takes place. The transition is either a cross over (at low μ) or of first order (at high μ). It is the goal of the present and future heavy ion experiment at RHIC and FAIR to study this phase transition at different locations in the μ, T plane and to explore the properties of the deconfined phase. It is the purpose of this contribution to discuss some of the observables which are considered as useful for this purpose.

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1. Introduction

The behavior of hadrons in an environment of finite temperature and density and the phase transition towards a deconfined phase in which quarks and gluons are the dominant degrees of freedom is a central topic of theoretical nuclear physics since many years. Detailed calculations have been revealed that hadrons react quite differently if the are brought in a dense and/or hot environment. Vector mesons change their width but not their pole mass when they are brought into a dense environment [1] whereas for K^+ mesons a substantial change of the pole mass is predicted [2] but the width remains small. At low temperature but high density K^- cannot be treated anymore as quasi particles having a quite complicated spectral function[3]. The different behavior of the different hadrons comes from their different interactions with their environment but many details of these interactions at finite density and temperature are not well known

Statistical calculations yield a chemical freeze out energy density of $1.1 GeV/fm^3$ for finite chemical potentials, well below the energy density predicted by lattice gauge calculation for the transition towards the deconfined phas where all hadrons become unstable. This deconfined phase is not a weakly interacting plasma, as one has thought for quite a time, but a liquid which can be described by hydrodynamics much better than ever expected. When applied to the scenario of an expanding quark gluon plasma these hydrodynamical calculations describe quite well the experimental observations if they start out from a strongly anisotropic initial state, caused by the geometry of the reaction partners, which expands while keeping local equilibrium.

From all these calculations we have a qualitative understanding of strongly interacting matter but from a quantitative understanding we are as far away as from an experimental verification of the theoretical predictions. The many body theory of hadrons in matter is complicated and many details are neither experimentally accessible nor theoretically known. Therefore theoretical predictions differ quantitatively. Due to the limited computer capacity also lattice gauge calculations have not converged yet to an exact temperature value at which the phase transition takes place. Even if in the next years progress will be made in the theoretical approaches the ultimate goal is to verify the predictions experimentally and to convert theoretical predictions into experimental facts.

In order to explore the properties of strongly interacting matter complicated experiments have been performed and designed - at RHIC, LHC and FAIR - in which in one single heavy ion reaction several hundred particles are registered in the detectors. When registered, however, all particles have to have their free mass and therefore one can only learn something about the properties of strongly interaction matter at high density/temperature if one understands the time evolution of the system between the high density phase and the detection.

Several ideas have been launched to asses matter properties at high density/temperature:

a) To measure resonances. The decay products reflect the particle properties at the point of disintegration which may be at finite density. If the decay products interact strongly these particles are sensitive to moderate densities only because the resonance cannot be identified if one of the decay products interacts another time.

b) To measure dilepton pairs. Because leptons do practically not interact with the expanding matter they may carry information on particles which have been disintegrated in a dense environment. This we discuss in section II.

c) To measure collective observables as discussed in section III.

d) To measure particles which can only be produced at the beginning of the interaction when the density is quite high because later the available energy is too low. This is the subject of chapter IV.

In this contribution I will critically review the significance of some experimental observables for the exploration of the high density zone at the future FAIR energies.

To study the sensitivity of the different probes on the properties of high density zone we employ the UrQMD model which has been successfully used to describe many of the stable and unstable particles observed at AGS and RHIC energies [4]. Details of this model may be found in [5].

2. dileptons

Using the UrQMD model we studied the time evolution of the ρ mesons which - due to their short life time - disintegrate while the system is still in contact. Their decay products, especially the dileptons, have been suggested as a possible source of information on the high density zone of the reaction. In Fig. 1, left, we display the time evolution of the density as a function of time for different energies, ranging from E_{lab} = 2 AGeV (SIS) to E_{cm} = 200 AGeV (RHIC). We display the average density in the rest system of the particles. Clearly, as expected, we see that with increasing beam energy the maximal density of the system increases. On the right hand side of the same figure we display the distribution of the densities at the space-time points at which a ρ meson disappears during the reaction, either because it decays (dashed line) or because it gets reabsorbed (dotted line). It is evident that the higher the density the higher is the chance that the ρ meson becomes reabsorbed. Thus most of the ρ mesons which decay (and with a certain probability can be observed as a dilepton pair in the detectors) are produced at a late time, long after the system has passed the high density. It is clearly visible that the ρ which disappear by decay come from a very low densities, close or below normal nuclear matter density. ρ mesons which are produced at higher densities become that fast reabsorbed that decay becomes a rare process. One can of course discuss the details of this approach, especially the properties of the ρ at high density. The conclusion that reabsorption and not decay is the dominant process at high densities does not depend on these details. Therefore, dileptons coming from a ρ decay are not sensitive to system properties at high densities. It is remarkable that the average density at the disintegration point of the ρ is at E_{lab} = 30 AGeV even lower than at E_{lab} = 2 AGeV caused by the higher particle multiplicity at higher energies. The fraction of ρ mesons which decay and of those which become reabsorbed we display in fig. 2 as a function of time. Comparing fig. 1 and fig. 2 we see that decay dominates only when the system is dilute. Thus dileptons coming from resonance decays are sensitive to system properties at low density only although they interact exclusively by electromagnetic interactions.

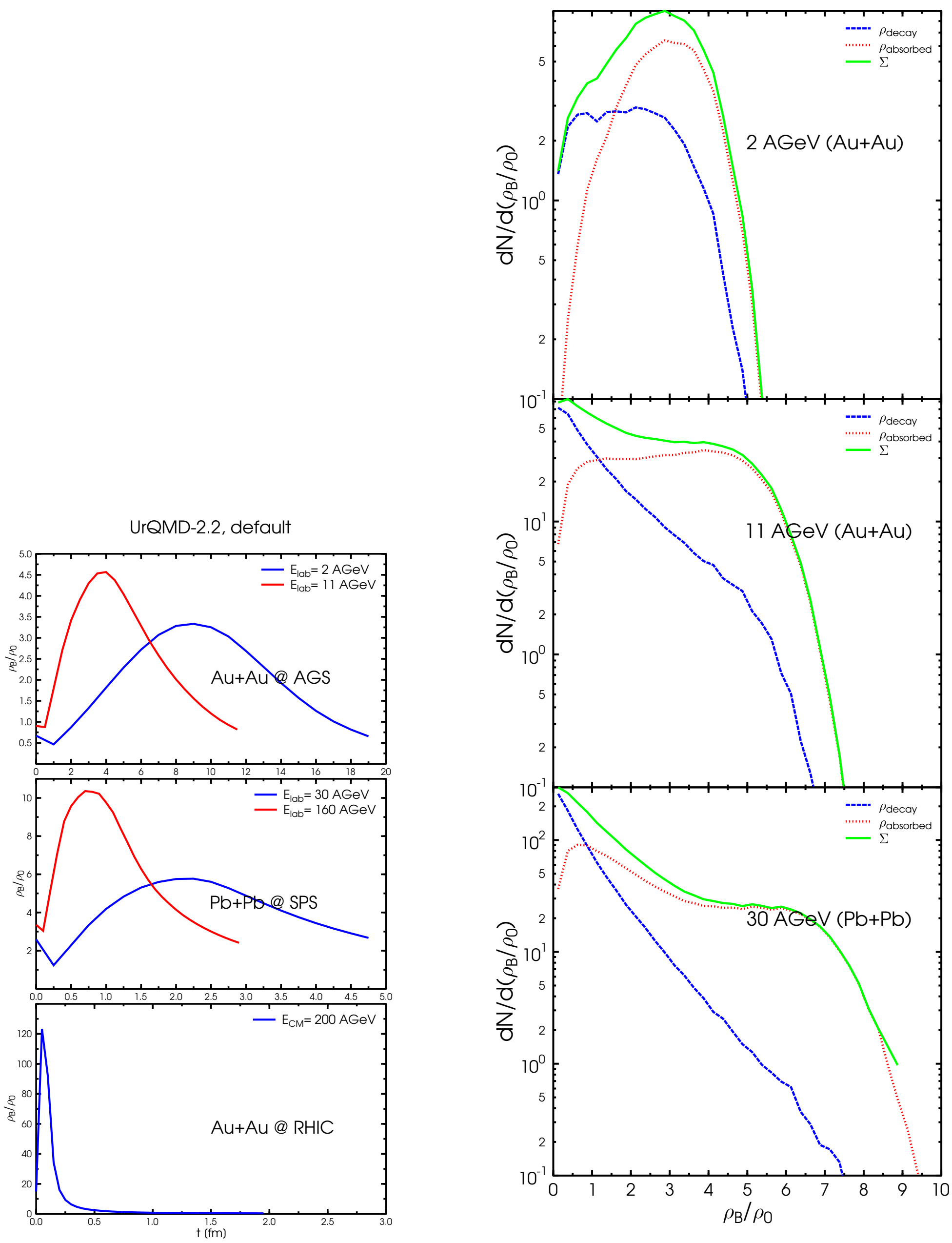

Figure 1: Left: Time evolution of the density of central heavy ion reactions for energies ranging from E_{lab}=2 AGeV E_{cm}=200 AGeV. Right: Distribution of the density at which ρ mesons disappear from the system, either by reabsorption (dotted line) or by disintegration (dashed line).

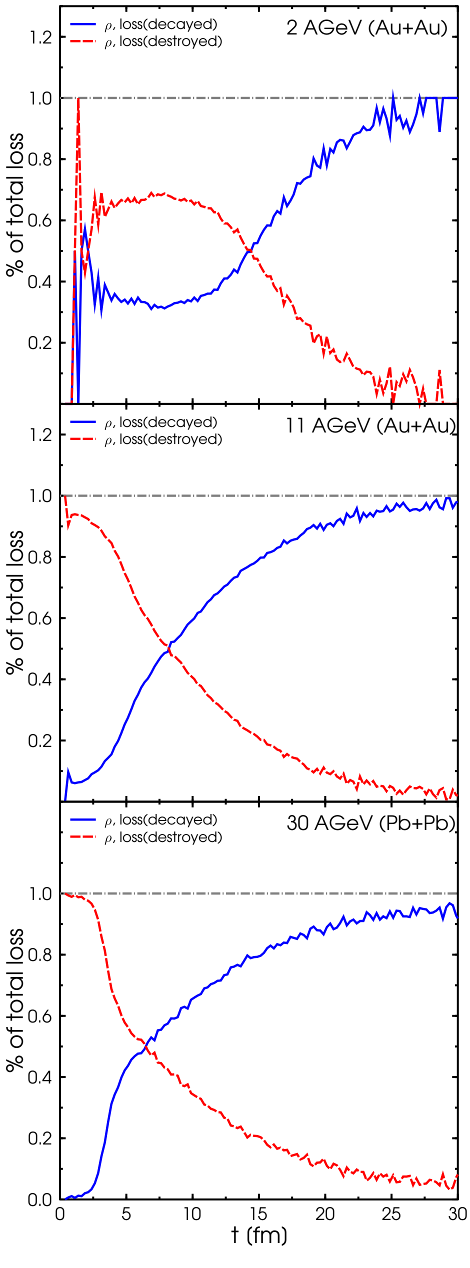

Figure 2: Fraction of the ρ meson which decay and which get reabsorbed (destroyed) as a function of time for 3 Beam energies between 2 AGeV and 30 AGeV.

3. Collective Observables

As said, at the energies we are interested in the system is strongly interacting. It is therefore possible that it acts collectively and that collective observables carry information on the high density state. Especially if the system passes the phase transition to deconfined matter where (most of the) hadrons are not existing anymore as stable particles collective observables are the only ones which may carry a direct information. There are many collective effects possible which are still explored. Here we concentrate on one particular collective effect which has been identified in ref. [7, 8] as a sign of the formation of a QGP. The phase transition towards deconfined matter may soften the equation of state. Such a softening would be visible in the excitation function of the in-plane flow,

$$p_x^{\mathrm{dir}} = \frac{1}{M}\sum_i^M p_{x,i}\,\mathrm{sgn}(y_i), \tag{3.1}$$

which decreases as a function of the beam energy much faster than expected from an hadronic equation of state. For standard equations of state this effect is maximal around the FAIR energies, where the system is expected to reach the softest point, i.e. has the lowest pressure to energy density ratio. Fig. 3 (from ref.[8]) shows the excitation function of p_x^{dir} in a hydrodynamical calculation. We see that after having reached a maximum, p_x^{dir} decreases to a minimum if the system becomes deconfined (QGP), whereas without the formation of a quark gluon plasma (had) p_x^{dir} there is not such a minimum.

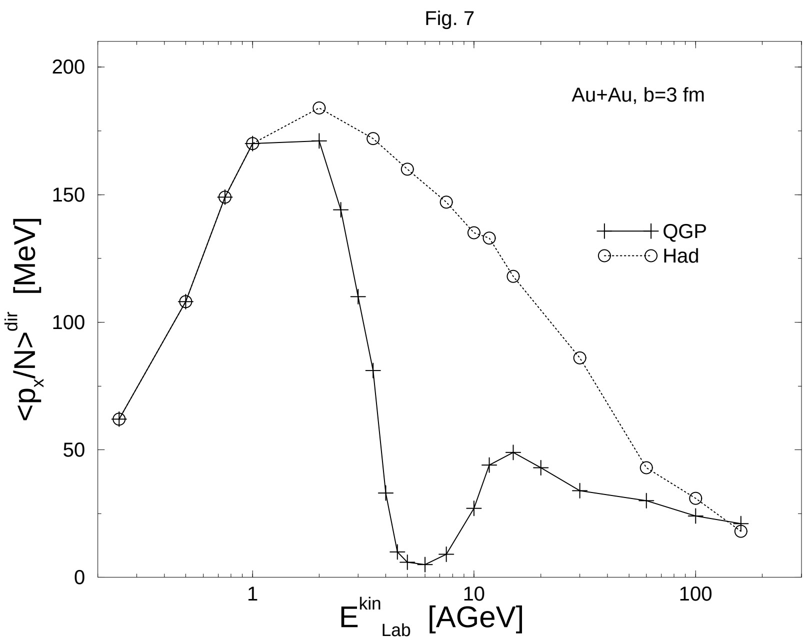

Figure 3: The directed flow, p_x^{dir}, as a function of beam energy for Au+Au–collisions at $b = 3$ fm. The full line (crosses) corresponds to hydrodynamical calculations using the EoS with phase transition, the dotted line (open circles) to those with the pure hadronic EoS. From ref. [8].

Thus measuring the excitation function of p_x^{dir} will bring the presence of a quark gluon plasma to light. Unfortunately this interpretation is laboring under a misapprehension. Using the more elaborate UrQMD model in which local equilibrium is not enforced but particles interact by known (free) cross sections we obtain the excitation function of $p_x^{\rm dir}$ shown in Fig. 4 [9].

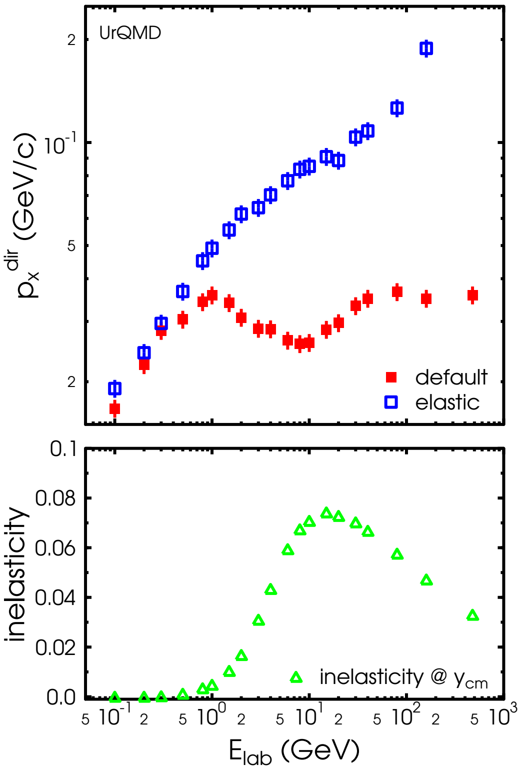

Figure 4: Excitation functions for central Au+Au (Pb+Pb) reactions. Top: Directed flow $p_x^{\rm dir}$ of nucleons with only isotropic elastic interactions (open squares) and with full elastic and inelastic collision term (full squares). Bottom: Inelasticity (open triangles), from ref. [9]

The reason for this form of the excitation function in UrQMD calculations is the change of the angular distribution of the nucleon-nucleon cross section with increasing energy and the increasing probability that resonances are produced which decay isotropically in their rest system. We see (top) that $p_x^{\rm dir}$ increases with energy if the nucleon-nucleons cross section were isotropic. The increasing anisotropy, seen in the NN data, produces, however, a maximum of $p_x^{\rm dir}$ followed by a decrease. At higher beam energies resonance production becomes important which is measured by the inelasticity

$$\text{Inelasticity} = \frac{\sum m_i}{E_{\rm total}} \quad \text{at}\, y_{\rm cm} \pm 0.5 \quad . \tag{3.2}$$

The isotropic decay of the resonances creates an increase of averge transverse momentum of the particles in the system. The reabsorption of the decay products depends on the azimuthal angle and causes an observable increase of the in-plane flow $p_x^{\rm dir}$. These two effects create in a realistic hadronic scenario an excitation function of $p_x^{\rm dir}$ which resembles strongly that obtained in hydrodynamical calculations if a quark gluons plasma is present. The lesson to be learnt from these studies is that collective observables in particular are complex and not easy to interpret and that one has to be extremely carefully to identify an experimental observation with one of the theoretically proposed reaction scenarios before having excluded that others may lead to the same predictions.

4. Charmed Hadrons

At SIS energies it has turned out that strange hadrons are a very good tool to investigate the system at high density/temperature. The reason for this is the fact that strange hadrons have to be produced and that at SIS energies only in the initial phase, shortly after projectile and target start to overlap, nucleon nucleons collisions are sufficiently energetic to overcome the threshold ($\sqrt{s_{thres}}$= 2.548 GeV, corresponding to a beam energy of 1.583 GeV in pp collisions) for the production channel with the lowest threshold ($NN \to K^+\Lambda N$). Once produced the s quarks can still be exchanged between a baryon and a meson but the probability that the s and $\bar{s}$ quarks annihilate is negligible. The charm multiplicity only gives information on the high density zone because the threshold and hence the production probability depends strongly on the properties of the strange particles at the production point. The initial momentum distribution is known from elementary collisions (and close to that expected from three body phase space). One can therefore compare the initial and final momentum distribution and use the difference to study the interaction of the strange hadrons with the surrounding matter during the expansion.

It is certainly tempting and also planned to follow the same strategy at FAIR energies by replacing strange hadrons by charmed hadrons. At the highest FAIR energies (E_{beam} = 30 AGeV, corresponding to a center of mass energy of $\sqrt{s} = 7.74\ GeV$ for a nucleon pair we are slightly above threshold for charm production process with the lowest threshold ($NN \to D^-(\bar{D}^0)\Lambda_c N$, $\sqrt{s_{thres}} = 5.073(5.069) GeV$) and therefore - as the strange mesons at SIS energies - charmed hadrons can only be produced initially in the high density zone. Before the promising perspective to use charmed hadrons for a study of the high density zone can lead to success a lot of work has to be accomplished.

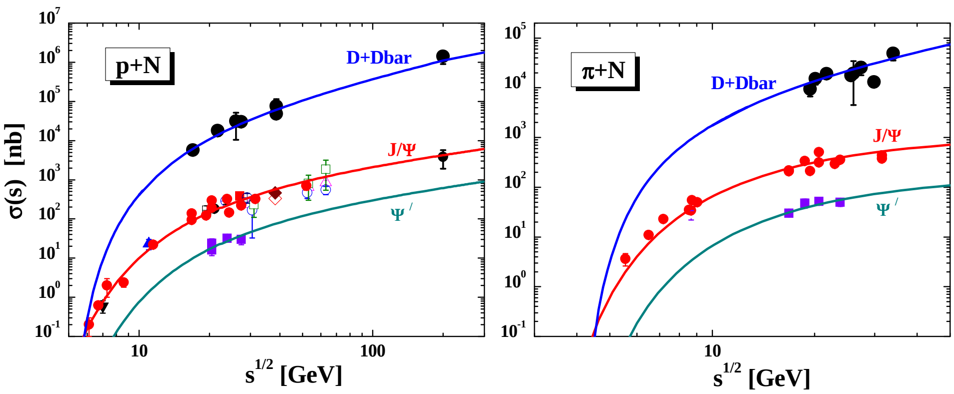

Figure 5: The cross section for $D+\bar{D}$, J/Ψ and Ψ' meson production in pN (left part) and πN reactions (right part). The solid lines show a parametrisations, whereas the symbols stand for the experimental data. The J/Ψ cross sections include the decay from χ_c mesons. From ref.[10].

The general problem is revealed in Fig. 5 and Fig. 6 which show the world data on charm production in elementary collisions, compiled in ref. [10, 11]. On can see directly that at the energies of interest at FAIR ($\sqrt{s} \approx 7\ GeV$) only J/ψ production has been measured which is less important at this energy because this cannel has an higher threshold than $NN \to D^-(\bar{D}^0)\Lambda_c N$. For the latter, dominant, channel not a single data point is known. Well above threshold many channels contribute and the few existing data points for $NN \to D^-(\bar{D}^0) + X$ are not of help to single out this

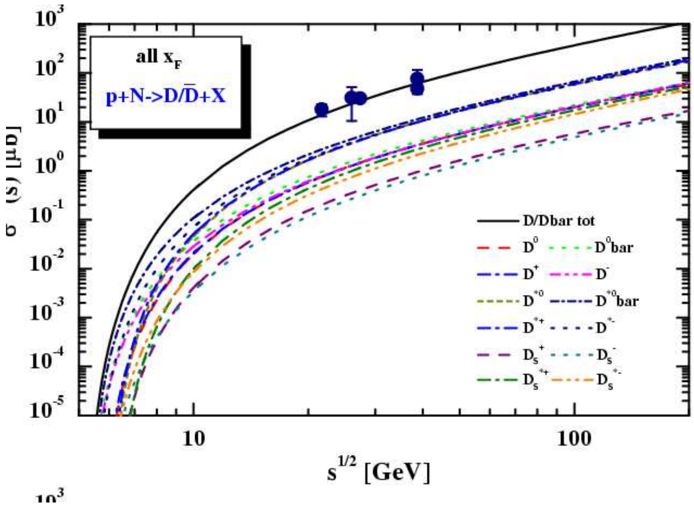

Figure 6: Cross section parameterizations for open charm mesons in comparison to the experimental data for pp. The upper solid lines denote the sum over all $D/\bar{D}$ mesons. From ref.[11].

cross section. There is an additional problem, already known from K^- physics at SIS. The Λ_c will have a considerable charm exchange cross section $\Lambda_c + \pi \rightarrow D + N$ which is, however, completely unknown. Due to this process the produced c quarks will be transferred to charmed mesons. Why is this of importance? All charmed hadrons disintegrate before they reach the detector and therefore one has to identify them by their decay products. The most promising are energetic electrons and the $K^-\pi^+$ channel. The branching ratio for disintegration into electrons of Λ_c (4.5 %) is much smaller than that of the corresponding D^- meson (17.2%). Therefore, without knowing the repartition of the c quark between mesons and baryons the observed electrons cannot be used to determine the charm production multiplicity in a heavy ion collision. This is also true, of course, for the $K^-\pi^+$ channel which is only sensitive to the c-quark entrained in a meson.

This lack of knowledge on the production cross sections of charmed hadrons in elementary collisions is also a very strong limitation for any theoretical prediction for heavy ion collisions. Dynamical simulation programs like UrQMD or HSD [10, 11] need these cross sections as an input quantity. With the present knowledge of these cross sections a reliable prediction for heavy ion collisions at FAIR energies is impossible. Once these cross sections are known, however, the excitation function of the multiplicity and hopefully also the experimental momentum distribution of the charmed hadrons which contain the desired information of the system properties at high density and temperature can be analyzed and - there I am quite sure - will reveal very interesting physics.

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